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NOVETTE FACILITY: ACTIVATION AND PRELIMINARY EXPERIMENTAL RESULTS*

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Abstract

The construction and performance of the Novette Laser/Target interaction system are described.

Introduction

When an extremely intense beam of laser light strikes a microscopic target containing deuterium-tritium fuel, it can generate an energetic plasma by imploding the fuel capsule. The rapid rise in temperature and density in the inertially confined D-T fuel produces a tiny but powerful thermonuclear explosion. The Lawrence Livermore National Laboratory has been the scene of active inertial confinement fusion, or ICF, research since 1969, with the goal of eventually achieving usable power from a future ICF reactor.

As recently as three years ago, controversy raged over the relative effectiveness of different lasers as fusion drivers. Today the preponderance of evidence favors a green to near-ultraviolet laser and we have assembled such a source for multikilojoule target experiments. The Novette laser-target interaction system fulfills this requirement by combining salvaged components from earlier LLNL lasers such as SHIVA, once the world's most powerful, with parts borrowed from Nova, a 100 TW device scheduled for completion in late 1984. [1]

Novette was assembled on an accelerated schedule in an existing building adjacent to the new NOVA laboratory. Novette includes a complete NOVA style control system, the refurbished SHIVA target chamber, and a full suite of target diagnostics. The Novette test bed construction began in January of 1982 and system activation was completed in thirteen months. Today, Novette routinely delivers 18 kJ infrared pulses 1 nsec in duration which are then frequency doubled and focused on to targets. During the past year a large body of data has been gathered concerning the performance of Novette as a system. In the following, measurements on Novette's beams, taken at several locations within the laser chains, will be compared to simulation calculations.

Each of Novette's two beam lines is optically very similar to a NOVA arm and so the emerging beams are 74 centimeters in diameter. Harmonic conversion takes place in two unique mosaic arrays of type II potassium dihydrogen phosphate crystals. The two ~ 4.5 TW green laser pulses so produced are concentrated onto targets by two, 74 centimeter aperture f/4 doublet lenses. Since the two pulses arrive at the target within five picoseconds of each other, a typical target may be irradiated essentially simultaneously from two sides by about 9 kJ in one nanosecond. About half of Novette's experimental time has been devoted to plasma physics studies whose aim is to better understand short wavelength laser-plasma interaction phenomena relevant to inertial confinement fusion. The balance has been divided between high density implosion research and non-local thermodynamic-equilibrium plasma experiments. In short, Novette provides a high energy density, flexible experimental facility which bridges the gap between SHIVA and NOVA while simultaneously probing each detail in the NOVA design.

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Design of Novette

In the course of ICF research, the laser program at LLNL has designed and built a series of successively more powerful and complex laser systems: first JANUS, then ARGUS, then SHIVA, now Novette, and soon NOVA. All of these lasers use or used chains of neodymium-glass amplifiers (in the form of sealed modules), and they all share the same fundamental design: a Master Oscillator driving a single-pass Power Amplifier (MOPA). Each of the lasers in this evolving series was designed to exploit the knowledge gained through experiments with its predecessor. Figure 1 is an optical schematic which shows Novette's relation to other LLNL MOPA system architectures. The fundamental design has been gradually improved through the use of increasingly reliable, efficient, damage resistant and cost-effective components. Along the way, a great deal has been learned about the propagation of high-power laser pulses in the dielectric media typically found in neodymium-glass amplifier chains. Novette and NOVA have been profoundly affected by the new insights into laser-plasma coupling phenomena gained only recently. Both theoretical and experimental studies indicate that coupling and, therefore, target performance improve significantly when the wavelength of the incident laser light is shortened below 1 µm. Accordingly, NOVA's design calls for harmonic conversion of the fundamental infrared laser pulse (with a wavelength of 1.053 µm) to green (0.526 µm) or to ultra-violet (0.351 µm) light before the beam is focused on to the target.

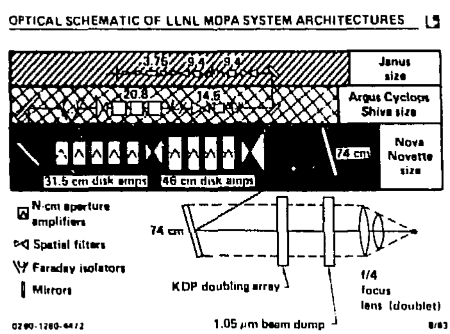

Figure 1

The design of the Novette test bed was premised on the requirements of the NOVA laser. Since the output of a repeatable, high-quality master oscillator is typically about .0001 J, NOVA's power amplifier must provide a gain of 1,000,000,000. In Novette, therefore, the weak pulse produced by the master oscillator first passes through a preamplifier, which consists of glass-rod amplifiers, beam-expanding spatial filters and beam-splitting elements, that produces two (in NOVA ten) parallel spatially uniform beams with energies of up to one joule each. At the master oscillator the laser beam is spatially Gaussian with a diameter at 10% of its maximum intensity of 1.5 mm. As it proceeds through the preamplifier, it is greatly expanded so that only the smoothest central region actually exits the preamplifier and is presented to the each of the arms indicated schematically in Figure 1. Seven beam expanding spatial filters separate stages consisting of rod and disk amplifiers with increasing apertures. The peak output flux from each stage is chosen to be near its operating limit. Propagation is controlled by these spatial filters in order to minimize local intensity fluctu tions and maintain the maximum laser flux below optical damage limits. Maximizing the "fill factor", or efficiency with which each amplifier's aperture is used, minimizes the peak laser flux that each optical component must tolerate to produce a given output.

In such a system the principal design constraint on the maximum energy delivered by each stage is the damage threshold of its optical components. This threshold not only depends on the purity of the optical medium but also on the optical surface, the pulse duration and the wavelength of the laser light. To raise the damage threshold in Novette, components like spatial filter lenses previously antireflection coated with dielectric films were replaced with borosilicate optics treated by a "neutral solution" process. [2] Such optics not only display excellent transmission (typically > 99.5%), but they also have 1 nsec pulse duration surface damage thresholds of 12 to 16 J/cm^2, approaching those of the polished glass substrate. This new technology has been tested in Novette on the large-diameter spatial filter lenses, windows and target focusing lenses in preparation for NOVA.

Since a major design goal of this type of laser is to maximize the output energy without damaging optics, one would like to propagate an ideal beam that exactly fills the power amplifier with an output flux just below the damage limit. However, such a beam does not propagate any useful distance without diffraction of the beam edges leading to constructive interference and thus regions of excessive optical flux. Novette's first power amplifier spatial filter, the one that expands the beam from its input diameter of 26 mm to 37.5 mm, is provided with a 2 mm diameter pinhole in its focal plane. The beam profile which emerges is nearly uniform with six faint rings. Succeeding spatial filters reimage or "relay" this beam on to the entrance lens of the following spatial filter and eventually on to the target chamber focusing lens. The net effect of this strategy has been to achieve a measured fill-factor of 85% in Novette which is substantially larger than that typical of earlier lasers (~ 70% or less).

In designing NOVA and Novette, the comprehensive, ab initio laser system simulation computer code, MALAPPOP, has proven to be invaluable as an estimator of peak fluxes impinging upon optical components. [3] MALAPROP calculates, limited by its resolution, the electric field experienced by each component in a hypothetical laser during a hypothetical shot. Realistic dirt and damage sites are introduced into each calculation in order to model typical operating conditions with this deterministic code. Staging decisions are driven by risk of damage assessments made using these computations. The components most vulnerable to laser-induced damage in Novette are the input lenses to the last two spatial filters. Neutral-solution antireflection coatings on these optics have survived unharmed after being subjected to over one hundred 1 nsec shots with average fluxes of five to sevon J/cm^2 and peak fluxes twice as large.

The conversion of laser light to its harmonics in nonlinear birefringent media is a well-known process which was first demonstrated more than twenty years ago. Because shorter wavelengths were shown to couple more effectively to fusion targets, considerable interest arose in using this upconversion process to generate short wavelength beams to irradiate fusion targets. Within the last three years, efficient conversion of 1.0 μm light to its 2nd, 3rd, and 4th harmonics in KDP for beams of up to 10 cm diameter has been accomplished in several laboratories. [4, 5 & 6] Currently, material and optical coating limitations restrict the harmonic fluxes tolerable in larger, high power, laser systems. The handling and focusing of the 2nd harmonic, 0.526 μm light, is possible with the same materials and coating technologies used for 1.053 μm light, and is therefore relatively straightforward. At the third harmonic, 0.351 μm, solarization of most optical glasses, low damage thresholds, and high nonlinear index of refraction are of concern. While solutions to these problems have been identified for NOVA, they could not have been applied rapidly enough to build Novette and meet an early experimental schedule. Novette was restricted, therefore to 2nd harmonic only.

Upconversion of Novette's output beams requires doubler optics with diameters greater than 74 cm. To meet this requirement, Novette's two frequency conversion arrays are mosaics of smaller crystals. Array architectures for Novette's initial operation were dictated by the size of available KDP crystals. One five element by five element array of 15 cm by 15 cm crystals and another three element by three element array of square crystals 27 cm on a side were built. In the Novette assemblies, the crystals and their "egg crate" support structures are sandwiched between neutral-solution processed windows which constrain the KDP crystals to ensure that they are all oriented within 100 μrad of each other.

MALAPROP has been used to predict the ultimate performance of Novette. Figure 2 summarizes the calculated capabilities of a single Novette beam. The upper curve illustrates the maximum 1.053 μm energy deliverable to the KDP array while the lower band represents an estimate of the highest (damage limited) 0.526 μm on target energy plotted versus laser pulse duration.

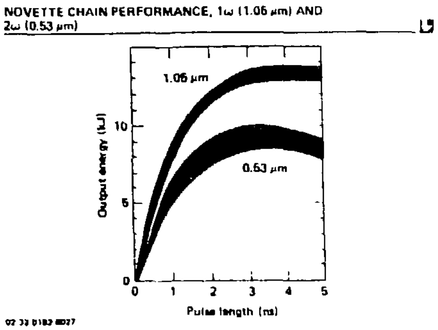

Figure 2

Construction of Novette

By late summer, 1981, wavelength scaling studies using the ARGUS laser were approaching completion. A survey of planar target plasma laser light absorption and subsequent X-ray emission had been carried out over a range of incident intensities and target materials. [7] The plasma physics community generally agreed that over the range of laser intensities of interest to inertial confinement fusion, 10 TW/cm^2 to 1,000,000 TW/cm^2, laser plasma coupling becomes progressively more dominated by the inverse bremsstrahlung absorption mechanism as the irradiating wavelength is reduced below 1 μm. While there were certainly many interesting experiments which might have been performed using ARGUS, it's main work was done. Near midnight on August 31, 1981, ARGUS irradiated its last target with a pulse of green light. The next morning, ARGUS disassembly began and what had been up to that time the two most powerful single arm laser amplifier chains ever built faded into history. So fragile are these lasers that even though no components were damaged, before noon it would have taken several months to reassemble and realign ARGUS. By the end of September, the bay was empty, stripped to the concrete. In the spring of 1982, the steel spaceframe was rising where ARGUS had stood and Novette construction was well underway.

Even as ARGUS was being dismantled, plans were set in motion to decommission the SHIVA laser system. SHIVA, the world's most powerful glass laser system, had operated successfully since late 1977 irradiating a wide variety of targets. SHIVA drove the targets that imploded to > 50 times liquid DT density in 1980 and it was with SHIVA that much of the plasma physics of indirectly driven inertial confinement fusion was unraveled. SHIVA's amplifiers, controls hardware and its capacitor bank were all required for NOVA. Novette would require two sets of SHIVA amplifier chain hardware by the spring of 1982. SHIVA's oscillators would have to move even sooner and SHIVA's target chamber was needed early in order to allow adequate machining time for adaption to the much larger Novette lens positioners. Before the new year, SHIVA had irradiated its last target. Gradually the components required for Novette were removed from SHIVA and refurbished. The remaining components rested quietly on their cradles on the SHIVA spaceframe until they were needed for NOVA.

During the summer of 1982, integration of the central control system software and operation of the smaller stages of the laser began. The large laser components with optical apertures of 30.5 cm and 46 cm began to arrive in August. By early September, Novette's 30.5 cm amplifiers delivered approximately four TW each in separate 100 psec shots. Next, the final 46 cm amplifiers and the two frequency conversion arrays were installed. These two 120 meter optical trains had to be folded in three to fit the 70 m by 15 m space previously occupied by ARGUS. Figure 3 shows Novette as it appears today.

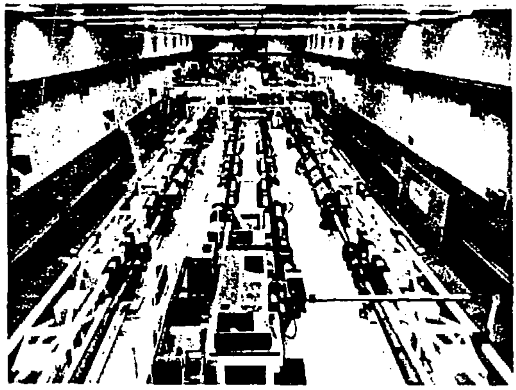

Figure 3a. Looking East

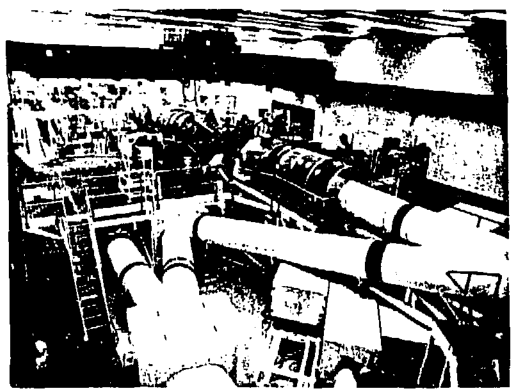

Figure 3b. Looking West

In January of 1983, a series of full power two beam shots were begun. On January 24th the highest powers yet recorded for a two beam laser were achieved; 25 TW infrared converted to 13 TW green for 100 psec. By this time Novette was already engaged in 100 psec X-ray laser studies. Figure 4 shows the history of Novette high energy laser shots in histogram form. The "target shots" indicated contributed to several plasma physics investigations while the "other" category contains all laser system diagnostic calibrations and laser related experiments.

Novette high energy laser shots

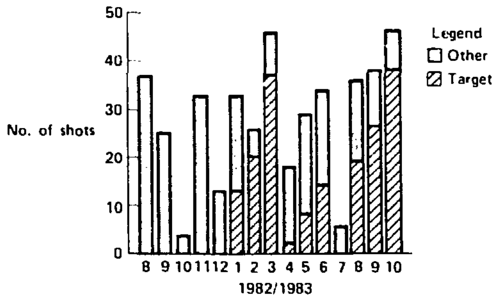

Figure 4

During a sixteen hour working day, Novette is fundamentally limited to about eight target shots by the cooling of its output amplifiers and subsequent laser system realignment. In practice, however, target and target diagnostic preparation and alignment have generally cut potential system usage by more than a factor of two. Dramatic reductions in productivity, measured by number of target shots per month, come at the end of an experimental sequence when an entirely new target type is first introduced. Initial 100 psec pulse duration X-ray laser studies were completed at the end of March, 1983, and wavelength scaling studies using one nanosecond pulses began. July was lost due to the appearance of optical damage in Novette's frequency conversion arrays when they were subjected to more than 1.5 J/cm^2. They were removed, cleaned and reassembled and the laser diagnostics were recalibrated at this time. One nanosecond operation resumed in August so that by October, with the shot rate still steadily rising, Novette's wavelength scaling study was done and an implosion series using targets of a similar geometry had achieved about 100x liquid DT density. The transition to cryogenic target experiments lowered the shot rate once again in November. Figure 4 suggests that shot rates in excess of 50 target shots per month could be achieved if a standard target design were used.

Performance of Novette

The laser pulse which will ultimately strike the target emerges from an actively mode-locked Q-switched neodymium:yttrium lithium flouride (Nd:YLF) oscillator as one of a train of about twenty pulses separated by 8 nsec. Each pulse in this burst exits this master oscillator at a time known with subnanosecond accuracy relative to the Q-switch time due in large part to very precise oscillator flashlamp control. Timed from the Q-switch trigger, the same pulse in the train is consistently selected by means of a Pockels cell gate. Novette's oscillator and switch out system has combined reproducibility of ± 2% in energy and ± 1% in pulse duration. It is the beam at this oscillator's plane output mirror which is optically relayed by the several spatial filters through the laser system to the target chamber focusing lens.

Triggered by Novette's computer control system, the master oscillator and preamplifier system provides all of the subnanosecond timing and trigger pulses required by the laser and target systems. In addition, this system measures the beam, automatically aligns it, and shapes the pulses in time and space. The devices installed in Novette's master oscillator system have provided temporally Gaussian pulses ranging in duration from 100 psec to one nsec and gated approximately rectangular pulses three to twenty nsec long.

At the output of the preamplifier, the beam is split into two beams whose relative timing is adjusted by means of variable path length sections and whose amplitudes are set using waveplate/polarizer pairs. The wings of the Gaussian beam have been truncated so that only the central 26 mm diameter portion is allowed to pass into the amplifier chains. A typical beam profile, measured just after the first spatial filter in Figure 1, is displayed in Figure 5.

NOVETTE BEAM AT CHAIN INPUT SENSOR

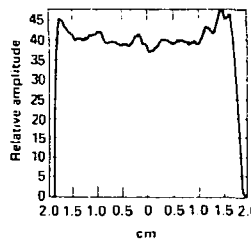

Figure 5a

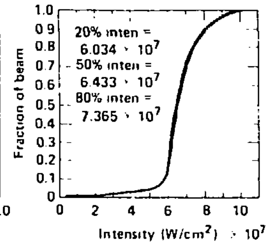

Figure 5b

Figure 5a is a scan across a diameter of this input beam and Figure 5b shows the distribution of intensities present in it. Each arm's first 28 cm long by 5 cm free aperture rod amplifier is therefore presented with a circular beam having an average intensity of about 64 MW/cm^2.

NOVETTE CYLINDRICAL DISK AMPLIFIERS, 92 mm AND 150 mm

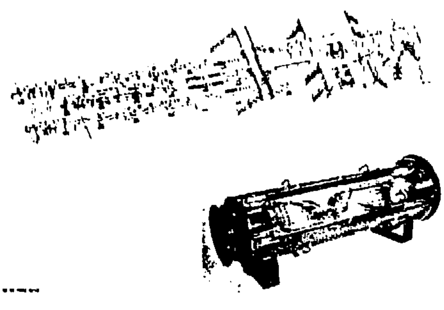

Figure 6a

Following the rod amplifiers, the beam passes through relaying spatial filter and glass disk amplifier stages of increasing size. The first two amplifier stages, having 9.4 and 14.5 cm clear apertures, *were removed from SHIVA and refitted with* phosphate glass disks. Figure 6 a) shows a typical SHIVA style cylindrical disk amplifier. The 20.8 cm diameter stage uses the more efficient box amplifier design, Figure 6 b). The large NOVA box amplifiers store approximately 2% of the electrical energy in the capacitor bank as inversion in the disks at pulse propagation time. *Following the 20.8 cm* stage, the beam is expanded to 31.5 cm, passes through the final Faraday rotator isolator in the chain and is turned by two mirrors which direct it

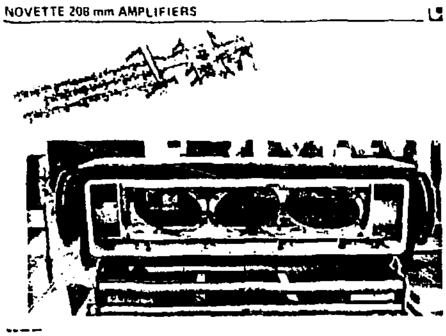

Figure 6b

down the final leg of the spaceframe which holds four 31.5 cm amplifiers and three 46 cm output amplifiers. Each of these amplifiers contains two disks, as indicated in Figure 6 c) and d) (NOVA will have one more amplifier of each size, shown dashed in Figure 1). Gain depeletion by amplified spontaneous emission, ASE, or nonresonant parasitic oscillations within each disk, impose a size limitation on glass disks. With well index matched absorbing cladding on the disk edges, ASE depumping limits the gain length product, $\alpha\ell$, along the major axis of the disk to between three and four. To preserve high stored energy, the disks in the largest amplifiers, those with 46 cm apertures, are split by an absorbing stripe along their minor axes.

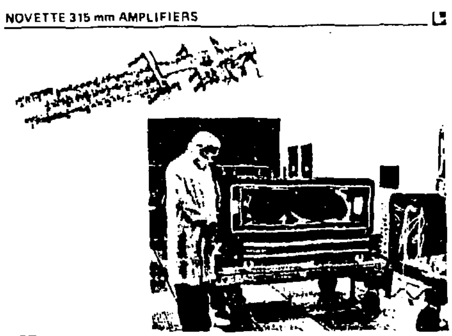

Figure 6c

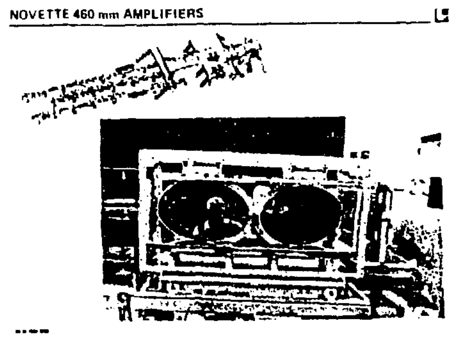

Figure 6d

As each amplifier was installed in Novette, its small signal gain was measured and these are listed in Table 1.

Table 1. Measure Amplifier Gains

Amplifier Type	Novette Nominal Gain
Rod (5.0 cm)	25.9
Disk (9.2 cm)	6.6
Disk (15.0 cm)	4.2
Disk (20.8 cm)	2.1
Disk (31.5 cm)	1.8
Disk (46.0 cm)	1.8

Since glass media are LHG-8 and LG-750 phosphate, the saturation flux encountered over the Novette operating range has been about 4.05 J/cm^2. The NOVA box amplifiers have flashlamps arranged only on the sides facing the disks. Each of the 46 cm amplifiers, for example, is pumped with a nominal capacitor bank energy of 500 kJ at 20 kV which gives them a stored energy of over 8 kJ.

Figure 7 compares experimental and calculated infrared output energies at the inputs to Novette's second harmonic converters for two pulse durations, 0.1 and 1.0 nsec.

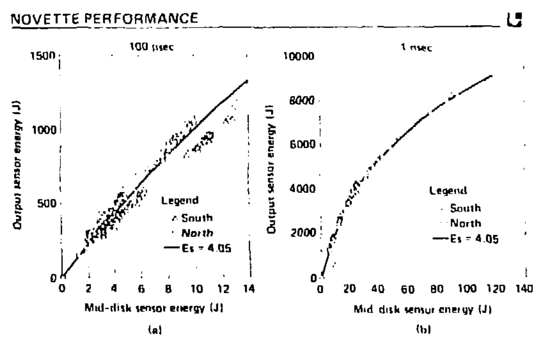

Figure 7

As Figure 7 shows, the 0.1 nsec pulses were never energetic enough to significantly saturate the two output amplifiers used at this pulse duration. The 1.0 nsec data, by contrast, were taken with three output amplifiers and somewhat larger spatial filter pinholes. Measurements show clear saturation of the 1.0 nsec gain in keeping with a theoretical calculation based on Ref [8].

Since November of 1982, photographs of the output infrared beams presented to Novette's second harmonic crystal arrays have been accumulated at the rate of about two per day. Virtually all of these images, like the 8 TW example in Figure 8, are quite uniform in appearance with slight evidence of nonlinear beam break-up. At 9 TW small-scale self-focusing effects are more cpparent. The prominent dark shadow bisecting each image is caused by the absorbing region in the largest (46 cm)

Novette output beam photos — 1 ns

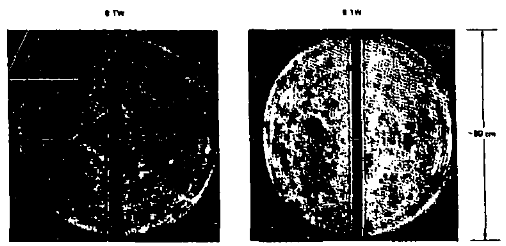

Figure 8

amplifier disks. Intensity dependent modulation grows as the output power increases, as quantified in Figure 9. The simulations contend that one nanosecond operation becomes unacceptably risky for Novette between 9 and 10 TW per beam.

NOVETTE 1ω INTENSITY AT SHG ARRAYS (100 psec)

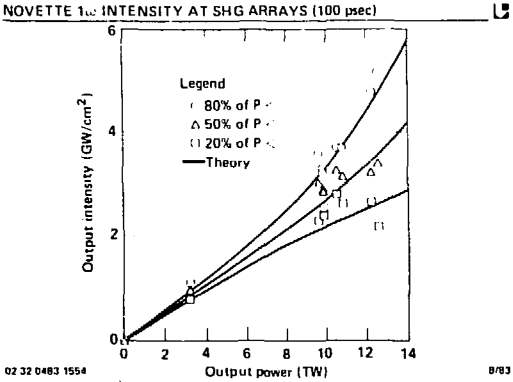

Figure 9

After leaving the 46 cm amplifier stage, Novette's two beams are expanded to 74 cm in diameter and reflected by mirrors over one meter in diameter up to the level of the target chamber, which they approach from opposite directions.

Before entering the lenses that focus the pulses on the target, each beam passes through an apodizer plate, the mosaic of KDP crystals and an infrared beam dump as shown in Figure 10. Bead blasted bands on the apodizer plate softly shadow the low damage threshold interstices between crystals in the second harmonic generation array which is located one meter downstream. By preventing diffraction from uncontrolled phase discontinuities between KDP crystals, this technique also shields the final focusing lenses from potentially damaging intensity ripples, but at a cost of ten to fifteen percent of the beam area.

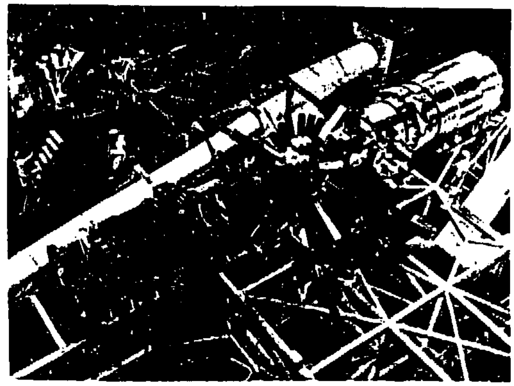

Figure 10

Almost every shot yields a measurement of the harmonic conversion efficiency and some of these data are plotted in Figure 11.

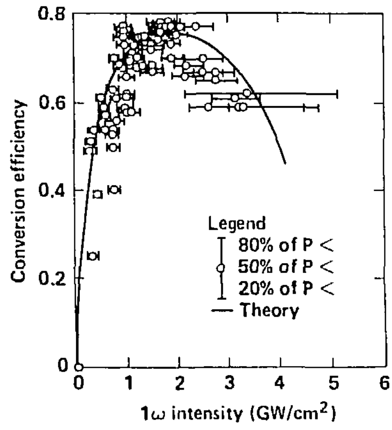

Figure 11

Corrected for beam area, array conversion efficiencies over 75% have been seen for incident infrared intensities of two GW/cm^2. The theoretical curve in Figure 11 was calculated for a single 1.8 cm thick type II KDP crystal detuned in angle less than 100 μm and presented with an infrared beam having the same intensity spread as Novette's. The mosaic is therefore behaving, by this measure, as if it were a single crystal. The beam next passes through a filter or "beam dump" which absorbs 99% of the remaining infrared light while passing 96% of the green energy. The converted light then proceeds through the f/4 doublet focusing lens, which concentrates it on the target.

Summary

Novette is the latest embodiment of the rapid evolution of powerful ICF laser systems. Each of its two relatively compact arms have exceeded the total output of all of SHIVA's 20 arms. Equally striking, Novette was assembled in well under a third of the time required to build SHIVA, needs less than half of SHIVA's manpower to operate and has achieved a shot rate on target twice SHIVA's. An evolutionary step of this magnitude in so short a time approaches a revolution in high power laser technology.

As a test bed for the NOVA laser, Novette has provided the first operational test of spit disk amplifiers and of harmonic generation in large-aperture, multi-element KDP crystal arrays. Novette has already largely completed the ICF experiments planned for it, delivering more than 9 kJ of 0.53 μm light to a fusion target in one nsec.

Acknowlegments

An undertaking of the size of Novette requires the sustained efforts of many dedicated workers. The design and construction of Novette were in large part accomplished by the NOVA project team headed by R. O. Godwin and W. W. Simmons. The NOVA lead engineers, E. S. Bliss, F. W. Holloway, C. A. Hurley, R. G. Ozarski, F. Rienecker, J. R. Severyn, M. A. Summers, E. P. Wallerstein, K. Whitham, their teams, and literally hundreds of U.S. firms spanning the full range of high technology industries devoted much of their time to this project during the last two years. Actual realization and operation of this laser system was guided by an "activation team", later called an "operations group", which has included O. C. Barr, D. G. Gritton, J. S. Hildum, B. C. Johnson, D. J. Kuizenga, D. R. Speck and G. J. Suski. We are all indebted to the Inertial Confinement Program leadership, J. L. Emmett and J. F. Holzrichter, for their guidance and to the Office of Inertial Fusion, DOE, for their continued enthusiastic support.

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